*Int. J. Impact Engng* Vol.14, pp.863–875, 1993
Printed in Great Britain

0734-743X/93 $6.00+0.00


# EXPERIMENTAL AND ANALYTICAL STUDY OF EARLY TIME MATERIAL PROCESSING, IN A COLLAPSING SHAPED - CHARGE LINER, USING "SOFTLY - RECOVERED" PARTIALLY - COLLAPSED COPPER LINERS

Dr. L. Zernow (1)*, Dr. E. J. Chapyak (2)

(1) Zernow Technical Services Inc., San Dimas, CA
(2) Los Alamos National Laboratory, Los Alamos, NM

## ABSTRACT

It is not yet clear what detailed deformation mechanisms enable copper shaped charge jets to exhibit the extraordinarily high ductility, which characterizes their dynamic behavior. The study described in this paper seeks to find some of these answers, by stopping the liner collapse process at various intermediate stages, and examining the grain structures in the partially collapsed liners.

Well characterized OFE copper shaped-charge liners, assembled into a cylindrical polycarbonate case, of constant length and volume, were partially collapsed, with reduced-weight cylindrical explosive charges. A series of increasing explosive charge weights were used to obtain progressively greater partial deformations on individual copper liners. The shock waves from the varying length explosive charges were coupled to the copper liners through intermediate water fill, which was in direct contact with the rear of the liners.

The series of partially collapsed copper liners was captured by "soft recovery" in low density polystyrene. Flash radiography prior to liner recovery, confirmed that the unexpected shapes of the recovered partially collapsed liners, actually existed prior to their entering the recovery medium and were not the result of the recovery process itself. This was an early concern when the unusual shapes of the recovered liners were first seen.

These shapes were also independently confirmed by a series of computations at Los Alamos National Laboratory, using MESA 2D.

A comparison of the photomicrographs of undeformed virgin copper liners and the series of partially collapsed liners, shows regions on the inner apex near the liner axis where plastic flow has occurred, with very substantial modifications (refinement and elongation) in grain structure even for the small deformations which barely change the overall liner shape.

Time dependent strain and strain rate computations, using LaGrangean tracer markers, indicate very large strain rates, between $3 \times 10^7$/sec. and $4.7 \times 10^7$/sec. in those regions with plastic flow where grain refinement and elongation are seen, even with very small overall deformation.

It is believed likely that this early time material processing and grain refinement, arising from the localized plastic deformation of the liner, plays a key role in preparing the liner material structure, so that it can exhibit the high dynamic ductility, characteristic of copper shaped-charge jets.

## INTRODUCTION

Although it has been known for well over fifty years that the copper in a shaped charge jet exhibits extraordinarily high dynamic ductility, the detailed physical mechanisms, based on sound fundamental physical models, which can quantitatively account for this phenomenon are not presently well understood, despite the fact that specific aspects of the problem have been extensively studied. The possible role of material strength and work hardening as well as the existence of a critical preferred disturbance wave length, which "grows faster than all others" thereby determining the average jet particle length after jet particulation, has been studied by Chou, et al (Ref. 1, 2). Scaling analysis has been studied by Walsh (Ref. 3). Instability criteria have been analyzed by Curtis (Ref. 4) and Pack (Ref. 5). Romero (Ref. 6a, 6b) has developed a stability parameter (L) which involves the ratio of inertial and plastic forces in the stretching jet. Very recently, Brown, Curtis and Cook (Ref. 7) have reexamined the role of asymmetry, which can also affect the particulation process by accelerating it.

The copper jet which is formed when a typical uniform walled copper liner is collapsed by an explosive charge (e.g. in a VIPER warhead), displays an approximately linear velocity gradient, with the front end of the jet moving at a velocity in excess of 9 km/sec and the rear of the jet moving at a velocity of about 2-3 km/sec. Under the action of this linear velocity gradient, the jet which remains in the solid plastic state, stretches like taffy, until it eventually particulates. The particulation process, which is preceded by quasi periodic ductile necking along the length of the stretching jet, defines the ductility limit by defining the maximum strain prior to fracture. Experimental observations of this stretching and particulation process, obtained by means of flash x-ray observations, indicate that a conservative estimate of the approximate average strain, at the time of fracture, can be higher than 10. This corresponds to 1000% strain. The approximate average strain is defined here as:

$$\frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

where $\frac{\Delta L}{L_0}$ = approximate average strain

$L$ = length of the continuous jet at the start of particulation

$L_0$ = length of the cone element (slant height of the cone) from which the jet was formed

$\Delta L$ = change in length = $(L - L_0)$ of the cone element from which the jet was formed

The observed dynamic ductility of the copper in the jet is therefore clearly in the superplastic range.

## OVERVIEW OF SIGNIFICANT FACTORS

There are several factors, both physical and geometrical, which can be immediately recognized as playing a potentially significant role in supporting and stabilizing such a high dynamic ductility. The elevated jet temperature and its effect upon the yield strength is clearly one of the physical factors that can affect the ductility (Ref. 8). The precision and uniformity of the liner wall thickness, as well as the coaxial symmetry of the liner, the explosive charge and the charge case, are typical of the geometrical factors which can separately affect the stability of the stretching process (Ref. 7).

There are many other more subtle factors which can also be seen as potential contributors (positive and negative) to the ductility limits. These would include the strain-hardening and strain-rate hardening properties of the copper which interact with the thermal softening properties (Ref. 9).

It is also suspected that the incidence of deformation induced porosity in the stretching jet (Ref. 10) especially in the necking regions, can also play a role in affecting how long the ductile stretching is maintained before fracture (particulation). The effect of dynamically introduced porosity on the particulation process is currently being examined computationally in another separate study (Ref. 11).

Finally, there has been continued wide ranging speculation regarding the physical source of the perturbations which result in the quasi periodic localized necking process. These perturbations and their growth ultimately define the stability and particulation of the stretching jet, and therefore the observed ductility limit, even in the absence of geometrical asymmetries. Compressibility effects and surface imperfections (e.g. machining marks) on the liner have been among the factors mentioned.

There have been preliminary attempts (Ref. 12) to account for the superplastic behavior of the copper jet by invoking the process known as dynamic recrystallization This is a strain rate sensitive process, which at sufficiently high strain rates, results in dynamic grain refinement, which may lead to the fine grain sizes normally associated with superplastic behavior. However, the attempts at the quantitative application of this mechanism to the analysis of the ductility of copper jets has so far not adequately accounted for the ductile behavior of these jets. Nevertheless, the concept itself is very attractive and warrants additional study. Part of the problem in evaluating such a model, is the previously unsuspected complexity of the material flow from the liner to the jet, which has recently been shown to exhibit large time dependent radial gradients of strain and strain rate (Ref. 13) as well as time dependent radial gradients of temperature (Ref. 8).

It is therefore evident that the current state of knowledge still does not provide a quantitative basis for a thorough understanding of the interacting combination of physical and geometrical mechanisms that permit the copper to undergo such large stable superplastic strains, in a shaped charge jet, before particulation. Qualitatively, the geometrical contribution of charge and liner symmetry to the jet stability is easiest to understand. The more difficult problem resides in the details involving the other physical mechanisms.

## MOTIVATION FOR THE PRESENT STUDY

It is very difficult to experimentally obtain time resolved dynamic information regarding the changing grain structure of the liner, as it is accelerated and deformed by the explosive charge, and ultimately flows into and out of the collision zone (stagnation region). It is even more difficult to experimentally obtain the time-dependent grain structure information as the flow leaves the stagnation region, dividing itself between the jet and the slug. These diverging flows are moving in directions $180^{\circ}$ apart, in the moving collision point coordinate system.

Some details of this complex flow (such as mass motion and temperature) can be accessed computationally (Ref. 13) but the 2D axially symmetric computational analysis presently provides no information regarding the transient time-dependent grain structure.; It

should be noted however that work at Los Alamos (Ref. 14) holds out the hope that at some future time, it might be possible to model some aspects of that part of the problem, related to the plastic deformation of a polycrystalline structure, in which the individual grain orientations are considered in order to provide information on the texture, before and after deformation.

In view of these difficulties, it appeared that any attempt to obtain even partial and approximate time-dependent grain structure information, could be beneficial. In thinking about this problem, the writer recalled some very early work he had done in the 1940's with S. Kronman, at the BRL (Ref. 15) in which copper shaped charge liners were partially collapsed by means of reduced mass explosive charges whose shock waves were attenuated and coupled to the liner through a water medium. The deformed liners were subsequently recovered in water. Increasing the mass of the explosive charge, permitted the partial collapse process to go progressively further until a set of liners was collected, displaying a wide range of deformations, which included the early collapse as well as the jetting and slug formation process.

These recovered liners were cut in half along the cone axis and mounted on a display board, which still exists today at BRL,(now ARL) as a matter of historical record. They were regarded for many years as interesting trophies which illustrated the nature of the shaped charge collapse process (Ref. 16) but, to the knowledge of the authors, partially collapsed liners were never studied quantitatively.

The partially collapsed liners could reasonably be regarded as approximate snapshots of the geometry of the progressive collapse process. It would however, not be reasonable to assume that the microstructure of the copper grains in those liners, truly reflected the instantaneous grain structure in the collapsed liner, at the time corresponding to the state of partial deformation in the recovered liner. However, despite this caveat, it was natural to contemplate what the deformed microstructure might show, especially in comparison with the original microstructure in the virgin unfired liner. It was this line of thinking that led to the experiments which are described in this paper.

## SUCCESSIVE STEPS IN THE DEFORMATION PROCESSING OF THE LINER MATERIAL DURING LINER COLLAPSE AND JET AND SLUG FORMATION

In order to help understand how and why the initial material properties of the shaped charge liner can influence the jet formation process, it is illuminating to consider a simplified view of how the liner material is being processed by shocks and by the severe plastic deformation during the liner collapse and jet formation process. The simplification involves ignoring the known radial variations in strain and strain rate discussed in Ref. 13. We will use the collision point coordinate system shown in Fig. 1A for this discussion. We will discuss primarily the processes pertinent to the partial collapse situation and will omit the details of the jet stretching and particulation process.

(1) As the explosive detonation proceeds, the liner is impacted obliquely by a detonation wave of 300-400 Kb amplitude. This initial interaction immediately results in shock heating of the liner and probably in the generation of numerous new dislocation sources and other structural defects, including twinning, stacking faults and possibly reduction of the initial grain size. The shocks induced in the liner material cause the heated liner material to bend toward the axis, and they can continue to generate high speed intersecting dislocations, leaving behind vacancies and other crystal lattice defects, as a consequence of the material deformation.

(2) The initial shock wave compression and shear stress causes shock heating of the liner material, and can drive it momentarily to temperatures higher than 600°C. As the shock pressure in the liner material decays, the material temperature falls to a lower residual temperature, which for copper, may be several hundred degrees lower than the initial shocked temperature, when the pressure has fallen to ambient atmospheric pressure.

(3) Under the impulsive loading provided by the detonating explosive, at pressure levels well beyond the yield strength of the liner material, it flows radially inward in a nearly hydrodynamic mode (see Ref. 17), undergoing increasing compression and shear deformation as it approaches the symmetry axis. This plastic deformation work causes the temperature of the liner material to increase again. In work hardening liner materials, like copper, this deformation can also induce work hardening, but the temperature increases also encourage thermal annealing of the induced lattice defects. Both processes can occur competitively.

(4) When the flowing liner material enters the collision zone, it undergoes further compression as well as a very drastic additional change of flow direction and very severe additional plastic deformation resulting in still more heating. It is believed that here, on the axis in the collision zone, is where the liner material attains its maximum temperature, which may be in the range of 800°C for a copper liner like the one in the VIPER charge. Most of the liner material originating in approximately the outer 75% of the liner thickness, goes into the slug and the remaining liner material coming from the inner thickness region of the liner, goes into the jet. This drastic divergence of the flow occurs close to the collision point and will be shown later in this paper to result in enormous localized strains and strain rates.

One might also imagine that for some liner materials, the temperature rise in the collision zone might be high enough to momentarily melt the liner material which might quickly resolidify as it left the collision zone. However, this seems relatively unlikely, on the basis of homogeneous heating computations, (Ref. 8) since the pressure in the collision zone is also very high. This would inhibit the melting process by substantially increasing the melting point by several hundred degrees C. There is both direct and indirect evidence that for materials like copper, the jet itself is essentially a plastically deforming crystalline solid. There has been no convincing evidence obtained so far to suggest even momentary melting in the collision zone (Ref.8) on the basis of homogeneous plastic deformation, although this conclusion awaits a more detailed examination of the microcrystalline region and central hole often found at the center of recovered copper jet particles (Ref.18) and a reexamination of the SESAME table for copper at lower temperatures and pressures, since this table was used in the computational analysis of the temperature distribution in the jet. There is also the possibility of attaining higher localized temperatures on slip bands, if the deformation energy is distributed inhomogeneously (Ref.19).

(5) The nature of the flow of liner material into the jet from a conical liner with a uniform wall thickness imparts a roughly linear average velocity gradient along the jet, with the forward portion of the jet moving faster than the rearward portion. The jet therefore continues to stretch plastically, like taffy, with its local diameter decreasing as the jet length increases. The plastic deformation work continues to be put into the stretching jet until just before the particulation process is completed. It is known that there are radial thermal gradients across the jet diameter, as well as along the jet length (Ref.8). There is also reason to believe that a large amount of microscopic porosity is being generated in the dynamically stretching jet material. Such a mechanism is needed to explain at least a part of the reduced material densities seen in flash x-rays of the jet prior to particulation (Ref.20,21,22). The temperature rise is clearly far too small to

explain the 15%-50% density reductions which are observed radiographically in the stretching continuous jet and in certain EFP observations.

The purpose of this relatively detailed review of the early thermal and deformation history during the formation of the jet and slug, is to indicate the overall nature of the changing environment to which the liner material has been exposed during jet formation. It provides an initial physical basis for interpretation of any information that can be extracted from a sophisticated and microstructural examination of jet particles captured by soft recovery, (Ref. 8) for comparison with the original liner material from which the jet was formed. Similarly, it is useful for interpretation of the microstructural examination of recovered partially collapsed liners, and their comparison with the virgin liner material in the unfired liner.

## THE OVERALL PROGRAM PLAN

### General

Experimental The program plan consisted of an experimental phase and an analytical phase. In the experimental phase, the initial virgin liners were carefully characterized in order to provide a baseline for comparison. The partially collapsed liners were "softly recovered" in low density polystyrene (1-2 PCF), sectioned and compared with the virgin liners.

Analytical In the analytical phase, the partial collapse experiments were examined computationally, using the MESA 2D Eulerian Code. The liner deformations which were predicted by the computations were compared with the observed deformations on the recovered liners. It should be noted that the computation did not attempt to resolve the time-dependent shock reverberation history within the liner walls.

### Specific Experimental Details

The shaped charge design selected for this partial collapse study is shown in Fig.2 and used a copper liner (OFE C10100). It was selected for numerous reasons, including the fact that this was the charge design used in the jet particle recovery experiments and the MESA 2D computation for the fully loaded charge had already been carried out in connection with the ongoing work on jet particle recovery (Ref.8). This simplified the set up for the computation of the reduced charge experiments, since all of the charge description parameters were already available and only the variable explosive charge description needed to be added. In addition, the characterization of the structure of the virgin unfired liners was also being carried out in connection with the jet particle recovery program (Ref.23). It was also helpful that the charge was of the proper size (33.3mm cone diameter) to make the flash x-ray observation and the "soft recovery" process easy to carry out, without modifying existing experimental set-ups. Finally, the requirements for metallurgical specimen preparation and examination were essentially identical and complementary to those being applied to the remainder of the jet particle recovery work.

The experimental set-up is shown in Fig. 3. The recovery medium was 24" in front of the charge. Flash x-ray was used to ascertain the configurations of the partially collapsed liner, prior to the time that it entered the recovery medium, which was a stack of low density polystyrene sheets(1-2 PCF), 12" x 12" x 1/2" thick.

The flash x-ray observations turned out to be a very significant experimental addition, since the shapes of the recovered partially collapsed liners were completely unexpected and were initially considered to be possibly deformed by interactions with the low density recovery medium. The availability of the flash radio-graphs however, clearly indicated that the recovered partially collapsed liner shapes were essentially identical to those seen in the flash radiographs, prior to their entry into the recovery medium. This conclusion was independently supported by the computational analysis, which will be discussed in more detail later.

### Computational Approach

The computational approach involved the use of MESA 2D, an Eulerian Code which has already been used quite successfully at LANL (Ref.24) for shaped-charge studies and in earlier portions of this program for jet temperature studies (Ref.8). The copper was treated as an elastic perfectly plastic solid with a 4.5 Kb yield stress. The Los Alamos tabular equation of state SESAME, was used for the copper and the standard JWL equation of state for the H.E. The computations were carried out until plastic deformation ceased and the residual motion of the partially collapsed liner consisted essentially of translation of the center of mass.

## THE EXPERIMENTAL DETAILS

The series of progressively increasing explosive charges, which were used to generate increasingly larger degrees of partial cone collapse, are described in Table I. These charges were placed at the rear of the interior body volume, as shown in Fig.2. The remaining volume, between the charge and the liner, was filled with water. By carefully inserting the detonator holder with the attached charge into the plastic body, excess water could be squeezed out around the rim of the detonator holder leaving a bubble free water fill, in contact with the liner, most of the time. Occasionally, a few small bubbles would form near the base of the liner as a result of chemical reaction of the water with the epoxy cement used to seal the liner in the body. Most of the modest asymmetry seen in some of the partially collapsed liners with the larger explosive charges, can be attributed to these bubbles in the water, since the charges were all fired horizontally and the bubbles therefore floated to the upper side of the charge.

## EXPERIMENTAL RESULTS

### General

The experimental results are divided into three parts. The first part contains the data which characterizes the initial virgin liners, which were fabricated by a forging process. The second part contains the data describing the geometrical configurations of the series of partially collapsed liners. The third part contains the data comparing the structure in the partially collapsed liners, with the original structure in the virgin unfired liners.

### Characterization of the Original Virgin Liners

The original liners were fabricated by a cold forging operation, using conical dies and a cylindrical work piece, beveled at the front. As a consequence, the portion of the liner which ultimately formed the apex of the liner, was less severely cold worked than the portion forming the remainder of the cone. Subsequent heat treatment of the forged liners,

was nominally designed to provide both fine grain liners and coarse grain liners. All liners were machined to final dimension after heat treatment.

The large variations in the degree of cold work between the apex and the remainder of the liner which are characteristic of this particular fabrication process, tended to obscure the effects of the heat treatment. As a result, it can be seen in Figs. 4 and 5 that while differences in grain size between the nominal fine and coarse grain liners are evident, they were much smaller than had been expected. In addition, the variation from apex to base on both the fine and coarse liners was quite large, with the lower portions near the base showing a small grain size and the upper portions nearer the apex showing a larger grain size, in both cases. However, the grain sizes in the upper regions of the "coarse" liners are only very slightly larger than in the corresponding locations on the "fine" liners, as can be seen from Fig. 4. In specific cases, however, where these observations concentrated at the apex, were repeated on new liners from the same batch, the average grain sizes through the apex region were indistinguishable between the "fine" and the "coarse" liners, as shown in Fig.4a. For the purpose of this paper, they will be considered to be indistinguishable through the apex region.

This particular characteristic of the large grains in the structure near the apex of both the "fine" and "coarse" liners provided an unexpected advantage, in assisting in the interpretation of the partially collapsed liner structures, because it provided a basis for separating the contribution of the shock wave from the contributions of the plastic deformation in causing visible <u>changes</u> in the grain structure. This will be discussed later, in more detail.

Experimental Details and Recovered Liner Identification

There were eight partial collapse experiments. Table II summarizes the individual identification numbers assigned to each of the eight recovered liners and the conditions of the experiment.

Structure Observed in the Partially Collapsed Liners

<u>Macroscopic Examination</u> In macroscopically examining the first two partially collapsed liners shown in Fig. 6, at 3x, the overall degree of deformation is seen to be relatively small in both cases. Liner 1F, collapsed with the 3.3 gram charge of Detasheet, as expected, showed a smaller degree of deformation than liner 2F, which was subjected to a 7.5 gram charge. Both showed observable thickening deformation and optical reflectivity changes on the polished section, in the apex region. They showed minor deformation along the sides. The polished cross sections of these two recovered liners which are shown in Fig. 6, reveal the reflectivity changes in the deformed region near the inner apex. Liner 8C, shown in Fig. 7, was also collapsed with 7.5 grams of Detasheet, in the same way as liner 2F. 8C clearly shows the start of a jet at the inner apex. Fig. 8 shows interior views of the inner apex region of recovered liners 2F and 8C at about 12x magnification, prior to sectioning. Both show evidence of significant apex thickening and the start-up of the jetting process. Liner 2F, the "finer" grained liner shows a smoother interior deformation surface than liner 8C, the "coarser" grained liner. Both show radial structures in the jetting start-up region, which are believed to be caused by compression folding instabilities which might occur more readily at the lower strain rates characteristic of a partial collapse process. Both also show circumferential circular structures which appear to be related to the machining marks on the liner.

Microscopic Examination of Liner 8C which was Collapsed with the Same 7.5 Gram Charge as Liner 2F When the apex region on collapsed liner 8C is examined at 50x magnification as shown in Fig. 9, an extremely interesting observation can be made, which reveals a transition in grain structure from the initially undisturbed grains in the outer rear of the apex region, to the deformed interior grains of the lower apex region, at the bottom of which the jetting process has started, and an emerging jet can be seen. The significance of this observation can be found in the fact that outwardly, the shock wave does not appear to have affected the appearance of the original grain structure, except in those regions in which plastic deformation and flow has occurred, as shown by the reflectivity change. In those deformed apex regions, below the outer apex and near the inner apex, the grains have clearly been elongated and severely distorted, as the plastic flow converged toward the axis, eventually generating the jet, seen in Fig. 9.

The unchanged outward appearance of the larger rear grains, which do not appear to have been disturbed by the shock wave passage, only means that at this shock pressure level, there are no optically visible effects of the shock wave, but there may very well have been dislocations, vacancies and other defects introduced, which would require special TEM techniques to be identified.

Microscopic Examination of Liner 1F In view of the observations in liner 8C, discussed above, the photo-micrographs for liner 1F were reexamined to determine if a similar grain structure modification and transition had occurred with the reduced 3.3 gram charge. Fig.10 shows that there was indeed a similar transition, but because the degree of plastic flow was smaller in liner 1F, the changes in the smaller deformed inner apex region were primarily in grain size. The plastic flow contours are just beginning to become visible near the inner apex region. The macrophotographs shown in Fig. 6 also show only small regions near the inner apex on liner 1F, in which there were noticeable reflectivity changes which define the plastic flow region. The corresponding reflectivity changes on liner 8C, in the inner apex region, were much larger and more pronounced.

Macroscopic and Microscopic Examination of More Heavily Deformed Partially Collapsed Liners It was now useful to examine the partially collapsed liners deformed with still larger explosive charges (14.4 grams and 21.4 grams of C-4 respectively). The first is almost twice as large as the charge used on liners 2C and 8C. The second is almost three times as large.

Fig.11 shows the macroscopic longitudinal cross sections of such partially collapsed liners after cutting, polishing and etching. Liner 3C (14.4 gram charge) shows the unusual "sombrero" configuration and liners 4C and 5F (21.4 gram charge) show the liner folded back toward the slug. As noted earlier, it was verified by flash x-ray that these unexpected odd shapes existed prior to soft recovery in the polystyrene.

The severely deformed region on the axis of the slug in liner 3C (Fig.11) again shows the typical reflectivity changes characterizing the new grain structure that exists in the region of severe plastic flow. The forward end (marked JET) shows what remained of the rear portion of the jet that was still attached to the slug after recovery. This will be discussed in the computational analysis.

The cross section of liner 6F (Fig.11) which was collapsed with the largest charge used (27.6 grams) shows an almost conventional slug, with the remainder of the liner which did not participate in the jetting process, folded back and still attached to the slug. The reflectivity changes have now extended to the forward jetting end, in the region that is

normally fully detached from the slug, when the liner undergoes cone collapse driven by a full explosive charge.

The microscopic examination of the rear of the liner 3C, in the region where the outer apex was originally located, is shown in Fig.12. This again showed a region at the upper outer apex, which retained the large grain structure seen in that region in the virgin unfired liners. This again indicates that the major optically observed grain structure modification occurs primarily in the regions where plastic flow has occurred. The passage of the shock wave through the outer apex has now, however, begun to leave the larger grains at the rear with the first evidence of slip bands and twinning.

The forward region containing the residual rear of the jet still left attached to the slug, is shown in Fig.13. Interestingly, this photomicrograph shows a fine grained structure in the tip with only a few of the elongated grains characteristic of the plastic flow region seen elsewhere to the rear on the liner axis. However, not far behind the residual jet tip, the elongated grain structure associated with plastic flow is again clearly visible and can be seen in the photomicrograph of the adjacent region behind the tip.

The same observations were made on recovered liners 4C, 5F, 6F and 7C. Fig.14 shows the interior view of liner 4C with the radial and circumferential markings. In addition, the tip of the residual jet shows the orthogonal shear traces, previously observed on many of the captured jet particles (Ref.8). The general observational result was essentially the same on the remaining liners. There was however, a trend for the length of the region of the larger grains to become smaller as the charge weight increased. In addition, as the charge weight increased, the slip markings and twinning in the larger rear grains became more severe. This indicates the increasingly severe effects of the shock wave passage. Fig.15 shows a 200x photomicrograph of the rear of the apex of liner 5F graphically illustrating the intragranular slip bands and the twinning at the outer rear apex, in the region of large grains. Finally, as the slug became longer, the region of convergent plastic flow became longer. However, in all cases, the front interior of the recovered liner, from which the jet emanated, clearly showed a very fine grain structure with very little of the interior flow process showing at the very tip where the rear of the jet separated from the slug. However, the orthogonal shear traces shown in Fig.14 were almost always present.

## INITIAL OUTPUT OF THE COMPUTATIONAL STUDY

The initial computational analysis of the partial collapse experiments which was carried out at the Los Alamos National Laboratory, using the MESA 2D Code, shows a good agreement of the predicted final partially collapsed liner configurations with the actual shapes of the recovered liners. Figs.16 to 18 inclusive, show the computed partially collapsed configurations predicted for the first four charges and can be compared with the actual cross sections of the recovered liners. The 27.5 gram charge has not yet been computed.

One of the surprises coming from the computations was the prediction of the actual jet formation process in all of the partial collapse experiments except the one with the smallest charge (3.3 grams). The recovered liners were weighed before firing, but, through an oversight, were unfortunately not reweighed after cleaning and before being sectioned for microscopic optical examination. Consequently, the amount of weight loss attributable to jetting could not be determined on these experimental runs, for comparison with the computational prediction. Needless to say, this omission will be corrected on future experiments.

The delay settings required to catch the slow moving final collapsed liners were so long (in the millisecond range) that the much higher velocity jet particles were no longer in the same field of view of the radiographs as the collapsed liners. Thus Fig.18 shows that the jetting, which is clearly visible in the computational output at 40, 80 and 120 microseconds is no longer seen near the collapsed liner at 160 microseconds and would be long gone from the field of view after a millisecond.

The analysis of the computations will continue in the future, with a more detailed study of the stress-time and pressure time histories to which various portions of the partially collapsed liners have been subjected. This will provide further quantitative insights regarding the observed response of the various portions of the collapsing liners.

## SUMMARY AND CONCLUSIONS

This work reported in this paper, represents a start at the problem of understanding, in phenomenological terms, the superplastic behavior of copper in a shaped charge jet.

An important preliminary conclusion is that very early in the collapse process, portions of the grain structure of the liner are being refined by the plastic flow processes, that start to move the liner material into the jet and the slug. These highly localized flows and the grain structure modifications that they cause, can be identified on both longitudinal and transversely sectioned samples of the partially collapsed liners, by a distinct change in reflectivity. In these regions, initially equiaxed grains in the inner apex region have been forced to undergo elongation and substantial diameter reductions, as a result of the material flow and the associated plastic deformation. The drastically reduced grain diameters essentially provide an early preconditioning which leads to the attainment of the fine grain structure, leading to increased dynamic ductility and ultimately leading to superplastic deformation of the stretching jet. The mechanism involved is primarily the plastic flow process which is effectively extruding the liner material into the jet.

A second observation is that the passage of the shock wave itself, through the liner material (e.g. at the apex) causes other types of modifications that depend on the shock amplitude. The behavior of the rearmost apex grains provide a convenient location for observing these effects. At the lowest shock amplitudes studied, the large, roughly equiaxed grains at the outer apex of the liners, (seen in Fig.4a in the virgin unfired liners) show little or not change in external appearance, whereas the grains at the inner apex of the same liner (e.g. 1F in Fig. 10 and 2F in Fig. 9) show very noticeable changes including grain deformation and grain refinement. The grains at the inner apex are of course, the ones which have undergone some plastic deformation as they start to converge and flow into the jet, to form the jet tip. The passage of the shock wave would still be expected to introduce various lattice defects into the material traversed, but these changes would not be readily visible in optical photomicrographs, when the shock amplitudes are low.

As the shock amplitude increases, one can begin to see in the nominally undeformed grains at the outer apex, the appearance of twinning and increasingly severe intragranular slip lines, as well as other evidence of the effect of the transient shock wave, although the grains at the rear do not appear to have undergone severe geometric deformation or plastic flow. This is indicative of the preliminary conditioning of the liner material, along the lateral surfaces of the liner, before it reaches the collision zone. Other evidence involving examination of the deflected liners prior to their entry into the collision zone indicates that grain refinement also occurs during the convergence process. For the larger charges,

one can find very large internal areas displaying the reflectivity change and the grain refinement (Fig.11). Converging flow lines become more extensive in the longitudinal sections in the center of the plastically deformed regions and the severity of the shock processing on the rearmost grains becomes quite dramatic (see Fig.15).

There is also additional study and analysis required to provide an interpretation of the significance of the radial and circumferential structures (e.g. as seen in Fig.14) which are generated early in the collapse process, and an evaluation of how they may affect the particulation process.

Further computational analysis of the flow process in the partially collapsed copper liners has been carried out by employing the LaGrangean tracer particle technique (Ref. 13) to track the strain and the strain rates in those specific regions of the liner apex which undergo severe flow and deformation during the early stages of the collapse process. These preliminary results indicate very large axial gradients in the strain and the strain rates, as one moves from the inner apex into the liner, toward the outer apex, for those interior regions along the axial direction where the liner material is separating into the jet and the slug. These are also the locations at which the metallurgical observations indicated severe flow and grain deformation. The local strain rates were found to attain surprisingly high levels, e.g. as large as 4.7 x 10 /sec, even in those liners which were only slightly partially collapsed with a small 7.5 gram charge of explosive. This analysis is now being reviewed. The data will be displayed at the poster session and will be the subject of a separate future paper.

## ACKNOWLEDGMENT

The work reported in this paper was supported under Contract N60921-89-C-0172 with funds provided by the U. S. Army (BRL), U. S. Navy (NSWC [WOL]) and DARPA. The computational work at the Los Alamos National Laboratory (X-3) was supported under the joint DOD/DOE Munitions Technology Development Program.

The sectioning of the metallurgical specimens and their optical examination was carried out by Paul Jacoy at the California Institute of Technology-NASA-Jet Propulsion Laboratory in Pasadena, California. The authors are indebted to Paul for his outstanding photographic work and for the extensive coverage of the photomicrographs.

## LIST OF REFERENCES

1. P.C.Chou and J. Carleone, "The Stability of Shaped Charge Jets", J.Appl.Phys.Vol. 48 4187-4195 (1977).

2. P.C.Chou, J. Carleone, W.J.Flis, R.D.Cicarelli and E.P.Hirsch, "Propellants, Explosives and Pyrotechnics", Vol.8, 175 (1983).

3. J.M.Walsh, "Plastic Instability and Particulation in Stretching Metal Jets",J.Appl.Phys,Vol.56 (7) Oct. 1984.

4. J.P.Curtis, "Axisymmetric Instability Model for Shaped-Charge Jets", J.Appl.Phys.Vol 61 (11) June 1987.

5. D.C.Pack, J.Appl.Phys.Vol 63, 1864 (1988).

6a L.A.Romero, "Instability of Rapidly Stretching Metal Jets", J.Appl.Phys.Vol.65(8) April 1989.

6b L.A.Romero, "The Stability of Stretching and Accelerating Plastic Sheets", J.Appl.Phys.Vol.69 (11) June 1991.

7. J.Brown, J.P.Curtis and D.D.Cook, "The Formation of Jets from Shaped-Charges in the presence of Asymmetry", J.Appl.Phys.Vol.72 (6) Sept.1992.

8. L.Zernow and L.E.Lowry, "High Strain Rate Deformation of Copper in Shaped Charge Jets", International Conference on High Strain Rate-Phenomena in Materials (EXPLOMET '90), San Diego, CA Aug. 1990.

9. R.G.Johnson and W.H.Cook, "A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures", Proceedings of the Seventh International Symposium on Ballistics, The Hague, The Netherlands, April 19-21, 1983.

10. L.Zernow, "Metallurgical, X-Ray Diffraction and SEM Studies of Individual Shaped Charge Jet Particles Captured by Soft Recovery-II,International Conference on Ballistics, Nanjing,PRC (1988).

11. Current work in progress under Contract DAAH01-92-C-R044.

12. A.H.Chokshi and M.A.Meyers, "The Prospects for Superplasticity at High Strain Rates: Preliminary Considerations and an Example", Scripta.Metall.-Vol. 24, 605, 1990.

13. L.Zernow, E.J.Chapyak, K.Meyer and R.H.Zernow, "The Origins of Liner Material in a Shaped Charge Jet Particle", Paper presented at the 13th International Symposium on Ballistics, Stockholm, Sweden, June 1- 3, 1992.

14. Sheila K. Schiferl, "Texture and Textural Evolution in Explosively Formed Jets", J.Appl.Phys Vol. 66 (6) 15 Sept. 1989.

15. L.Zernow, S.Kronman, "Experiments Generating Partially Collapsed Copper Shaped Charge Liners" 1950 (BRL-Unpublished).

16. W.P.Walters, J.A.Zukas, "Fundamentals of Shaped Charges", John Wiley & Sons, 1989

17. E.M.Pugh, R.J.Eichelberger and N.Rostoker, "Theory of Jet Formation by Charges with Lined Conical Cavities," J.Appl.Phys.,Vol.23,May 1952,Page 532.

18. L.Zernow, "New Results from the Examination of Jet Particles Captured by Soft Recovery", 11th International Symposium on Ballistics, Brussels, Belgium (1989).

19. D.E.Grady and J.R.Asay, "Calculation of Thermal Trapping in Shock Deformation of Aluminum", J.Appl.Phys. Vol.53 (11) 1982.

20. F.Jamet and G.Thomer C.R.Acad. Sci., Ser.B 279 (1974) 50.

21. F.Jamet, "Mesure de la densite d'un jet de charge creuse en cuivre par radiographie-eclair" - R101/76 - Institute St. Louis, 1976.

22. R.R.Karpp, "Direct Dynamic Measurement of the Material Density Within a Shaped Charge Jet", Proceedings of 37th Annual Bomb and Warhead Meeting, Charleston, South Caroline, May 1987.

23. Current work in progress under Contract N60921-89-C-0172.

24. J.Bolstad and David Mandell, "Calculation of a Shaped Charge Jet using MESA-2D and MESA-3D Hydrodynamic Computer Codes", LA Report 12274, UC-000, Feb.1992.